

Final Technical Report

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**Initiations, Shut-offs and Restarts of Repeating Earthquakes at Parkfield, CA:
Post-seismic Changes in Deep Fault Properties**

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ABSTRACT

The objective of this project was to improve our understanding of spatially and temporally varying seismic processes that reflect post-seismic changes in fault zone properties related to slip stability transitions and their potential impact on earthquake hazard estimation. The core seismological observations of post-seismic change in this project are the extended quiescence (shut-downs) and reactivation of deep repeating earthquake (REQ) sites observed to the northwest of and following the 2004 Parkfield M6.0 earthquake and following a similarly located M4.7 event in 1993. The observations of multi-year shut-downs and eventual restarts of REQ activity on a creeping fault following larger events suggests that the REQs may be sensitive to load-rate dependent transitions between stable and unstable states and that their behavior may be useful for gauging the potential participation of generally aseismically slipping (creeping) fault in coseismic rupture during larger adjacent earthquakes.

We applied advanced seismic analysis techniques and data (cross-correlation pattern matching scans, continuous data, phase-coherency analyses, low-frequency relative moment calculations, relocation and analysis of source mechanism data) to REQ and general seismicity data and compared them with geodetic, and finite source inversion results to more accurately define the relationship of the observed REQ and associated seismicity changes within the context of the structural and time varying deformation and stress fields following larger events in the Parkfield area. This was done to improve our understanding of the likely causes for the REQ changes and to constrain changes in fault properties related to slip-stability transitions in the fault zone, potentially leading to improved time-dependent estimates of larger earthquake potential within or adjacent to creeping fault.

We have identified a relatively small but unusual location on the SAF (an ON-OFF zone) where both repeating earthquake (REQ) sites and nearby background seismicity effectively shut-off for periods lasting up to 8 years (i.e., several times the average REQs recurrence intervals) and subsequently turn-on again. Seemingly paradoxically, the shut-off periods occur during post-seismic periods associated with larger nearby earthquakes when other, more typical, REQs and seismicity greatly accelerated in their rate of recurrence/occurrence, in accord with accelerated rates of post-seismic slip and aftershock activity. The return of REQ activity and seismicity in the ON-OFF zone following the shut-off periods indicate that the ON-OFF process is transitory and that the REQ sites are not destroyed, but rather persist or re-emerge over the longer-term. Expected fault slip in the ON-OFF zone during the shutdown periods is not represented by inferred REQ slip, nor can it be accounted for by accelerated REQ slip either before or after the shut-off period.

Our results suggest that the REQ sites either slipped coseismically by up to 40 cm with the rupture of nearby larger event mainshocks or became sites of aseismic/stable slip for an extended period of time (i.e., during the ~ 8 year shut-offs), slipping ~ 40 cm, without generating REQ events or significant non-REQ seismicity. The absence of modeled coseismic slip from seismic and geodetic inversion in the ON-OFF region during the nearby mainshocks favors the later possibility, that the REQ sites transitioned into a stable-mode of slipping, and then recovered after an extended period of time. A possible mechanism for this behavior is an injection of high-pore pressure from an external source who's pressure decayed back to pre-mainshock levels after ~ 8 years. No evidence exists, however, for such a source. Transitory pore-pressure elevation from a flash-heating process is too short in duration to explain the ~ 8 year shut-off periods in the ON-OFF zone.

SIGNIFICANCE

Characteristically Repeating Earthquakes (REQs). REQs are believed to represent the repeated ruptures of the same fault asperity or patch. Small patches of low magnitude REQs are loaded to failure by aseismic slip on the surrounding fault surface [Nadeau and Johnson, 1998; Schaff et al., 1998], and their locations indicate regions where fault creep is taking place. The distribution of REQ patches associated with the weak slipping zones in turn tend to outline or delineate regions of larger locked fault at depth that could participate in future larger earthquakes (Burgmann et al., 2000; Schmidt et al., 2005). Relationships have also been developed that allow estimates of the rate of fault creep surrounding the REQs to be made based on the REQs frequency of repetition and magnitudes (Nadeau and Johnson, 1998; Nadeau and McEvilly, 1999 and 2004).

The objective of this project was to improve our understanding of spatially and temporally varying seismic processes that reflect post-seismic changes in fault zone properties related to slip stability transitions and their potential impact on earthquake hazard estimation. The core seismological observations of post-seismic change in this project are the extended quiescence (shut-downs) and reactivation of deep repeating earthquake (REQ) sites observed to the northwest of and following the 2004 Parkfield M6.0 earthquake and following a similarly located M4.7 event in 1993. The observations of multi-year shut-downs and eventual restarts of REQ activity on a creeping fault following larger events suggests that the REQs are sensitive to load-rate dependent transitions between stable and unstable states and that their behavior may be useful for gauging the potential participation of generally aseismically slipping (creeping) fault in coseismic rupture during larger adjacent earthquakes.

Shut-downs of REQ sites following the devastating 2011 Tohoku M9 earthquake off Japan have recently been reported (Uchida, 2012). It is clear that the expected acceleration of nearby REQs on creeping fault following this event did not occur in many locations. This and the unexpectedly large size of the M9 event suggest that previously creeping (i.e., REQ bearing) portions of the Tohoku event rupture zone may have transitioned into an unstable state and participated in and contributed to rupture of this anomalously large earthquake. Historically, other unexpectedly large and/or complex earthquakes have also occurred (e.g., 1920 Haiyuan, 1960 Chile, 1988 Spitak, 1992 Landers, and 2012 Indian Ocean quakes). These uncharacteristic earthquakes all ruptured through hypothesized segment boundaries that appear to impede rupture during typical earthquakes on these fault systems, and such hypothesized boundaries include normally stable, creeping fault.

A recent model proposed by Noda and Lapusta (2013) suggests a possible mechanism for transitional behavior from stable to unstable fault slip in which stable, rate-strengthening behavior at low slip rates can combined with coseismic weakening due to rapid shear heating of pore fluids during large earthquake rupture to allow unstable slip to occur on fault segments that otherwise creep aseismically between events. The question then arises as to whether or not a similar mechanism can explain the shut-downs and restarts observed for several REQs observed in the Parkfield area. To help address this question, this project investigated several related issues and alternative hypotheses:

1) What was the spatial extent of the shut-down/restart (i.e., ON-OFF) behavior following the larger events?

2) Do the ON-OFF REQs occur on the SAF proper or are they occurring instead on closer-in but distinct subsidiary faults with possibly different orientations and mechanisms? If so, the response of these REQs may reflect perturbations in the stress field induced by the larger events instead of processes related to changes in slip stability that could influence extent of rupture of future large quakes on the main through-going SAF.

3) Is the ON-OFF behavior of the REQs consistent with other nearby seismicity having similar but less identical waveforms? In general, the ON-OFF behavior or the REQs should be mimicked by other seismicity in the same general area. However, because identification of REQ events requires they continue to generate nearly identical waveforms, apparent shutdowns of REQs could result if a significantly large change in REQ rupture distorts their waveforms and makes them unrecognizable as REQs proper. Indication of such distortions would be apparent ON-OFF behavior of the REQs that is not accompanied by similar ON-OFF behavior of surrounding less-similar seismicity.

4) Were the sites permanently shutdown by the larger M6.0 and/or aftershocks or did the sites eventually become reactivated, indicating a return to creeping behavior in the fault surrounding the REQs?

5) Did the REQs stop because the fault on which they occur participated in the coseismic rupture of larger nearby events, and what can be inferred from the time to recovery (i.e., time to restart) of the sequence following the 1993 M4.7 and 2004 M6.0 earthquakes with respect to the amount of coseismic slip and/or overshoot that may have taken place on the otherwise creeping fault? In this case the expected response of the REQ sites is largely dependent on the characteristics of the coseismic rupture. If the cumulative coseismic slip is large in the REQ zone, return of identifiable REQs at the same site are not expected (i.e., the site is permanently shut-down). This is because opposing sides of the REQ patch have slipped past each other to the point where re-rupture is no longer identifiable do to distortion of the waveforms they generate (i.e., relative to earlier waveforms). If coseismic slip does not distort the REQ patches and their generated waveforms and significant overshoot takes place (i.e., coseismic slip is > slip-deficit), then a delay in reactivation of the REQ site is expected, and the length of the delay will depend on the degree of the overshoot and the rate at which tectonic forces make up the overshoot and reload the REQ patch.

6) Can the ON-OFF properties of REQs be considered the result of a transient clamping/strengthening process on the fault (possibly due to a jog or kink in fault geometry) that delays the release of post-seismic slip in the shut-down region? Indication of this would be and shut-down of the REQ activity during an initial clamping stage followed by significantly accelerated REQ activity when unclamping takes place to allow for the release the slip deficit accumulated during the clamping period. Transient clamping/unclamping of a fault jog suggests a mechanism by which normally creeping fault can be coerced into a rupture arresting segment boundary during coseismic rupture, possibly returning to a creeping state at a later time.

7) Did the REQs stop because accelerated post-seismic slip of extended duration coerced the REQ patches into a stable-state. Indication of this would be a gap in REQ activity during the post-seismic period until post-seismic slip rates decayed to those comparable to pre-seismic rates when the REQ sites were active.

WORK PERFORMED

Updates of REQs and associated similar events: Thirty-nine REQ sequences located around the northwest extent of the Parkfield M6 rupture zone were updated through the end of 2014, resulting in a final catalog of REQ sequences containing 1095 repeated microearthquakes ranging in magnitude from M-0.7 to M2.1 (**Figures 1 and 2**). Updates were based on waveform similarity and were performed by scanning reference event templates through continuous borehole data recorded by the High Resolution Seismic Network (HRSN). The scanning approach optimizes completeness of the small magnitude repeats during the continuous recording period of the HRSN (2001.5 to current) by eliminating reliance on multi-station detection algorithms. The measures of waveform similarity used were maximum cross-correlation values among at least 3 channels at 3 stations. Third quartile maximum cross-correlations among all recording stations and channels for both P and S phase arrivals were typically 0.98 or higher. Double-difference relocations of the events using hypoDD (Waldhauser, 2001) were also performed to help confirm effective collocation of the REQ events. Additional similar events associated with but not classified as repeats due to lower waveform similarity were also cataloged (5556 additional events). Third quartile maximum cross-correlations for these events were typically 0.8 or higher. These events generally occur within a few hundred meters of the REQ template events, have essentially the same mechanism, and when present distribute themselves on a planar structure that includes the REQ site and is generally parallel to the San Andreas Fault (SAF). However their magnitudes vary by up to 2 magnitude units from that of the reference. The similar events were used to evaluate the possibility of distorted waveforms from changes in rupture on REQ patches taking place due to the occurrence of larger nearby events.

Common Reference Frame: When possible, we placed the locations of our REQ sequences into a common reference frame with the overall seismicity listed in the USGS's double-difference real-time (DDRT) catalog (Waldhauser and Schaff, 2008). We found that this could be done for 39 of our 42 REQ sequences by cross-referencing events in the REQ catalog with at least one event location in the DDRT catalog (**Figure 1**). The common reference frame was used to evaluate the spatio-temporal relationship of the REQs with other seismicity in the area and the possibility of the ON-OFF REQs occurring preferentially on subsidiary fault structures or at fault jogs, as defined by the DDRT seismicity.

Source Mechanisms: The magnitudes of the REQs studied were of relatively small magnitude ($< M2$). Smaller magnitude REQs repeat more frequently, providing greater temporal resolution and a greater spatial density of REQ sites. However, mechanisms at these smaller events are typically less well constrained due to fewer phase picks and station coverage. When available, we evaluated the first motion source mechanisms of the REQ and associated similar events through cross-reference with the mechanisms listed in the ANSS on-line catalog. We confirmed that, though the waveforms for the REQ events were nearly identical, the catalog mechanisms had significant scatter among the REQ events. However, within the range of scatter, the catalog mechanisms for all the REQs were consistent with rupture on a SAF aligned fault plane. Evaluation of the mechanisms of the larger, more-well-constrained, events in proximity of the ON-OFF zone also showed mechanisms consistent with SAF parallel rupture.

Analyses: A variety of analyses of the spatial, temporal, size and mechanism distributions of the REQs and seismicity in the area were carried out to address the questions/hypotheses posed above. Their results are presented in the following results section.

RESULTS

Project results are presented below in the context of how they address the question posed in the significance section.

1) What was the spatial extent of the shut-down/restart (i.e., ON-OFF) behavior following the larger events?

The distribution of ON-OFF REQs are limited to a small region of no more than ~1 km dimension (red, **Figure 1**). The region is also located along the fault about 2 km northwest of the 1993 M4.7 and an apparent repeat of this M4.7 event as an aftershock of the 2004 Parkfield M6.0 earthquake. An additional, slightly shallower M4.9 aftershock of the 2004 event also occurred approximately 2 km further northwest (i.e. ~ 4-5 km northwest of the 1993 M4.7 rupture). The non-REQ seismicity in the region also shows a similarly limited region of ON-OFF behavior following 1993 M4.7, M6.0 and larger M6.0 aftershocks. However the degree to which seismicity was shut-off is noticeably greater following the M6.0 and its aftershocks (**Figures 3**).

2) Do the ON-OFF REQs occur on the SAF proper or are they occurring instead on closer-in but distinct subsidiary faults with possibly different orientations and mechanisms?

The locations of the REQs within the common DDRT reference frame show the REQs are consistent with their occurrence along the main SAF zone as defined by the overall pattern of DDRT located seismicity (**Figure 1**). Within their range of scatter, the catalog mechanisms for all the REQs also show that they are consistent with REQ rupture on a SAF parallel fault plane. Together, these observations greatly reduce the likelihood of the REQs preferentially occurring on subsidiary faults of non-SAF alignment. Evaluation of the mechanisms of the larger, more-well-constrained, events in proximity of the ON-OFF zone also showed mechanisms consistent with SAF parallel rupture. Consequently it seems unlikely that the ON-OFF behavior of the REQs and general seismicity in the area are the result of differences in fault orientation or placement on subsidiary or secondary faults.

3) Is the ON-OFF behavior of the REQs consistent with other nearby seismicity having similar but less identical waveforms?

As noted above the ON-OFF behavior of the REQs is generally mimicked by other seismicity in the same general area. However, some low-level seismicity does occur during the shut-off periods of the REQs. Because identification of REQ events requires they continue to generate nearly identical waveforms, apparent shut-downs of REQs could be the consequence of significantly large changes in REQ rupture leading to distortions in waveforms that make repeats unrecognizable. It is possible that some of the low-level seismicity may actually be REQ events with distorted waveforms.

To help evaluate the likelihood of events with distorted waveforms masquerading as non-REQ events, we examined the ON-OFF behavior of the similar events with their associated REQ sequence events during the period of scanned, continuous seismic data (2001.5 to the end of 2014). While the waveforms of events within REQs are similar with each other to cross-correlation values of 0.98 or higher, the criteria for similar events we used was relaxed to 0.80 cross-correlation. This resulted in over 5-times the number of similar events being considered in the ON-OFF zone than are classified as REQ events. These similar events also generally occur within a few hundred meters of the REQ site, have essentially the same first motion mechanisms, and distribute themselves on a planar structure that includes the REQ site and that is generally parallel to the strike of the San Andreas Fault (SAF). Their magnitudes, however, can vary by as much as ~2 magnitude units. Consequently the similar events represent a much more relaxed similarity criteria than that used for REQ identification, and allow for a wider range of waveform distortion to be considered. Nonetheless, **Figure 4** shows that within the ON-OFF zone there was no evidence of similar events that might represent REQs with distorted waveforms to the relaxed criteria described above.

4) Were the sites permanently shutdown by the larger M6.0 and/or aftershocks or did the sites eventually become reactivated, indicating a return to creeping behavior in the fault surrounding the REQs?

Figure 2 shows that as of the end of 2014, two of the four updated REQ sites were reactivated in 2013 and have had several repeats since that time. The other 2 sites have not as yet begun to repeat. Following their 1993 M4.7 shut-off, the repetition of these same 2 sites did take place, and their reactivation of these 2 sites was delayed slightly relative to the other 2 ON-OFF. This suggests that further monitoring may reveal eventual reactivation of these two sites as well. Alternatively, these 2 sites may have been permanently shutdown due to effects of the 2004 M6.0 earthquake. This seems less likely due to the fact that all four of the ON-OFF sites are relatively closely spaced and the expectation, therefore, that they should experience similar effects from the M6.0 rupture. Therefore, we interpret the reactivation of the REQ sites to represent re-initiation of deep fault creep in the ON-OFF zone after a delay of ~ 8 years since the 2004 M6.0.

5) Did the REQs stop because the fault on which they occur participated in the coseismic rupture of larger nearby events, and what can be inferred from the time to recovery (i.e., time to restart) of the sequence following the 1993 M4.7 and 2004 M6.0 earthquakes with respect to the amount of coseismic slip and/or overshoot that may have taken place on the otherwise creeping fault?

In this case the expected response of the REQ sites is largely dependent on the characteristics of the coseismic rupture. If the cumulative coseismic slip is very large in the REQ zone, the REQ site may be expected to shut-down permanently (i.e., return of identifiable REQs at the same site would no longer occur due to dramatic changes in the character of rupture at the sites) This might occur either because opposing sides of the REQ patch have slipped past each other and no longer rupture as previous REQs at the site or because the state of slip stability has changed from unstable (generating earthquakes) to stable (creep).

Alternatively if coseismic slip in the ON-OFF zone is less dramatic and permanent shut-down of the REQ site did not take place, then the slip deficit in the ON-OFF zone

may have been erased during coseismic rupture and possibly a slip-surplus may have built-up if significant overshoot took place. Under these circumstances, a delay in reactivation of the REQ site would be expected, with the length of the time to reactivation being dependent on the rate at which tectonic forces reload the REQ sites to their strength thresholds and/or the amount of the overshoot that may have taken place.

On the other hand, it is possible that the post-seismic effects from the larger events changed the slip-stability at earthquake sites in the ON-OFF zone from unstable to stable sliding. This might be due to either an accelerated aseismic slip rate during the post-seismic period or due to a long duration weakening of the fault in the ON-OFF zone (See item 7 below). It is also possible that a combination of recovery of load to REQ strength thresholds and the decay of longer-term fault weakening effects may be a play.

From **Figure 2** it is clear that the REQ sites did not permanently shutdown due to nearby the larger events, indicating that if coseismic rupture occurred in the ON-OFF zone, it was not 'very large'. Based on the REQs just beneath the ON-OFF zone that experienced more typical post-seismic response to the 2004 M6 mainshock, ~ 40 cm of fault slip occurred during the 8 years between the M6 event and reactivation of the ON-OFF REQ sites. Assuming the stability states of the REQ sites remained the same (i.e., they slipped seismically) then ~ 40 cm of REQ slip is missing and could be assumed to have occurred coseismically. Assuming a tectonic loading rate of 3 cm/yr, for this portion of the SAF, then an overshoot of 3cm/yr x 8yr or 24 cm of slip can be inferred to have occurred and an additional 16 cm of slip-deficit can be inferred to have existed just prior to the M6 event in the ON-OFF zone.

6) Can the ON-OFF properties of REQs be considered the result of a transient clamping/strengthening process on the fault (possibly due to a jog or kink in fault geometry) that delays the release of post-seismic slip in the shut-down region? Indication of this would be a shut-down of the REQ activity during an initial clamping stage followed by significantly accelerated REQ activity when unclamping takes place to allow for the release the slip deficit accumulated during the clamping period. Transient clamping/unclamping of a fault jog suggests a mechanism by which normally creeping fault can be coerced into a rupture arresting segment boundary during coseismic rupture, possibly returning to a creeping state at a later time.

The locations of the seismicity and REQs in **Figure 1** suggest the existence of a slight fault jog adjacent to and just to the southeast of the ON-OFF zone. It is not apparent, however, that a significant acceleration in REQ activity occurs once reactivation takes place. This argues against a process of post-seismic clamping and unclamping, with release of pent-up post-seismic and tectonic deficit accumulation following the shutdown period.

7) Did the REQs stop because accelerated post-seismic slip of extended duration coerced the REQ patches into a stable-state? Indication of this would be a gap in REQ activity during the post-seismic period until post-seismic slip rates decayed to levels comparable to pre-seismic rates when the REQ sites were active.

In effect, this question asks if the REQ patches weakened during post-seismic shut-off periods (i.e., whether or not the unstable (earthquake generating) REQ sites transitioned into an entirely stable (aseismically slipping) state) due to increased fault loading rates

due to accelerated post-seismic slip from larger nearby events. **Figures 2, 3 and 4** support this hypothesis.

Reduced rates of fault healing during post-seismic periods of a few hundred days have been reported and attributed to such a load related fault weakening (Marone, Nature, 1998; McLaskey et al., Nature, 2012). However, these effects have only been able to account a lowering of stress-drops released in repeating earthquakes, and not the complete cessation of REQ rupture. If fault healing were the process at play in the ON-OFF zone studied here, then the absence of healing would have to be complete and have a duration lasting up to 8 years. This suggests that the frictional and healing properties of the ON-OFF zone are very different from typical properties assumed for earthquake faults.

Another possible mechanism might be a dramatic increase in pore-pressure possibly unrelated to the rate of post-seismic loading signal. Such a mechanism would effectively reducing fault strength at the sites of seismicity to levels unable to sustain significant slip deficit and earthquake occurrence for an extended period. Because an increase of pore-pressure due to flash heating of fault zone fluids is a short-term process, it cannot explain the long-term (~ 8 year) weakening of the fault zone required to explain the REQ data. Hence if weakening due to increased pore-pressure were at play, it would require an alternative source for the high-pressure fluids.

CONCLUSIONS

We have identified a relatively unusual location on the SAF where both repeating earthquake (REQ) sites and nearby background seismicity can shut-off for periods lasting several times the REQs typical recurrence intervals. Seemingly paradoxically, the shut-off periods occur during post-seismic periods associated with larger nearby earthquakes when other, more typical, REQs and seismicity accelerate in their rate of recurrence/occurrence in accord with accelerated rates of post-seismic slip and aftershock activity. The REQ activity and seismicity in these ON-OFF zones return after the shut-off periods, indicating that the ON-OFF process is transitory and that the REQ sites are not destroyed, but rather persist over the longer-term. Expected fault slip in the ON-OFF zones during the shutdown periods is not represented by inferred REQ slip, nor can it be accounted for by accelerated REQ slip either before or after the shut-off period.

These observations suggest that the REQ sites either slipped coseismically with the rupture of nearby larger event mainshocks or became sites of aseismic/stable slip for an extended period of time without generating REQ events (i.e., during the ~ 8 year shut-offs). The absence of modeled coseismic slip in the ON-OFF region during the nearby mainshocks favors the later possibility, that the REQ sites transitioned into a stable-mode of slipping, and then recovered after an extended period of time. A possible mechanism for this behavior is an injection of high-pore pressure from an external source who's pressure decayed back to pre-mainshock levels after ~ 8 years. No evidence exists, however, for such a source. Transitory pore-pressure elevation from a flash-heating process is too short in duration to explain the ~ 8 year shut-off periods in the ON-OFF zone.

A long-term post-seismic shut-off of the fault healing process in the ON-OFF zone, arising from accelerated post-seismic loading, is an alternative hypothesis for the observed behavior. However evidence for this processes leading to the necessary complete cessation of seismic rupture of the REQ sites for an extended ~ 8 year period has never been reported.

A few other anomalous REQ sites exhibiting similar behavior relating to the 2004 M6.0 were observed in the limited REQ dataset used in this project. A more comprehensive search and analysis of REQ and associated seismicity would provide a clearer picture of the distribution and proportion of ON-OFF zones along the SAF and provide additional constraints for interpretation and modeling of active SAF properties.

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FIGURES

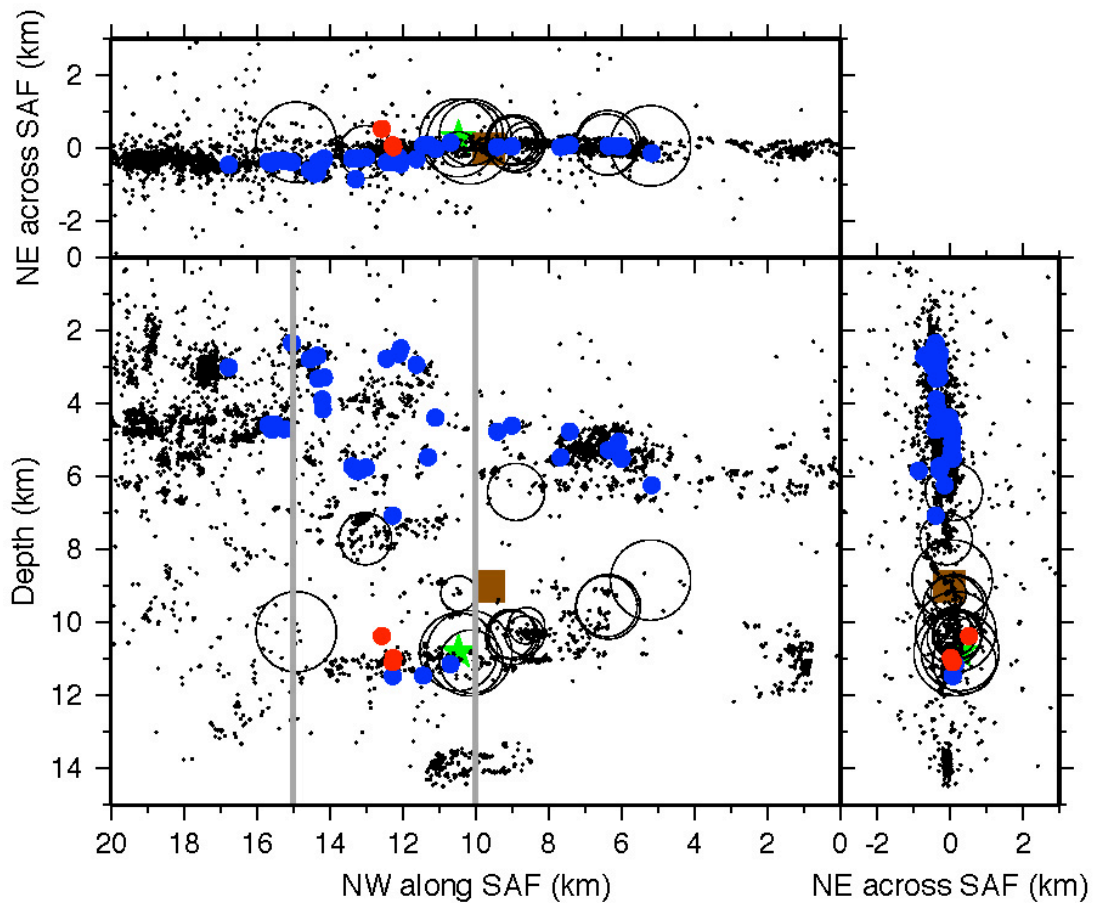


Figure 1. Locations of REQs (colored circles) and other seismicity ($<M3.5$ points, ≥ 3.5 circles) in the DDRT reference frame. Top panel is map view. Bottom left is along fault depth section. Bottom right is across fault depth section. Red are REQs showing ON-OFF behavior. Blue are other REQs used in the study. Green star is location of the 1993 M4.7 earthquake. Gold square is hypocenter of the 1966 Parkfield M6.0 essentially defining the northwest end of the 2004 Parkfield M6.0 mainshock rupture. Gray vertical bars show focus area used in **Figures 3 and 4**.

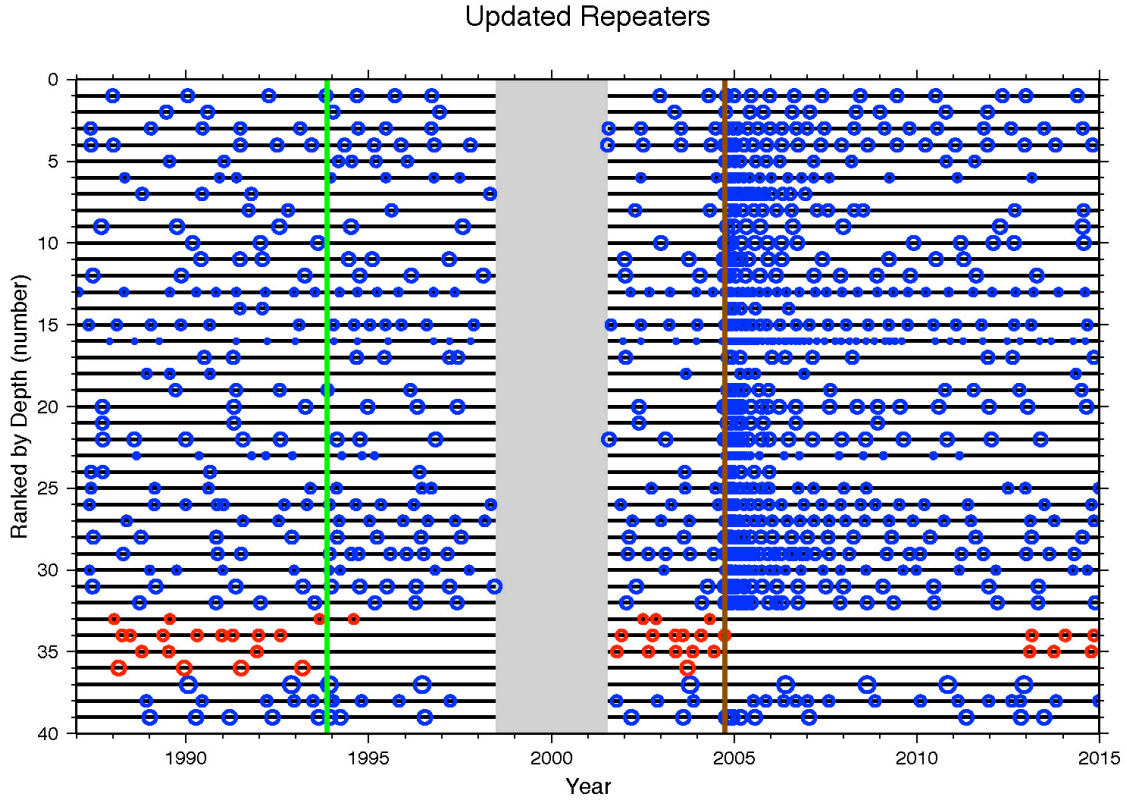


Figure 2. Time-line of updated REQ sequence events ranked by depth, top to bottom → shallow to deep. Red are sequences exhibiting ON-OFF behavior. Blue are other REQs studied. Green line is time of the 1993 M4.7 event. Brown line is time of 2004 Parkfield M6.0 mainshock. Gray band is period when the HRSN borehole network was off-line and no repeaters were cataloged.

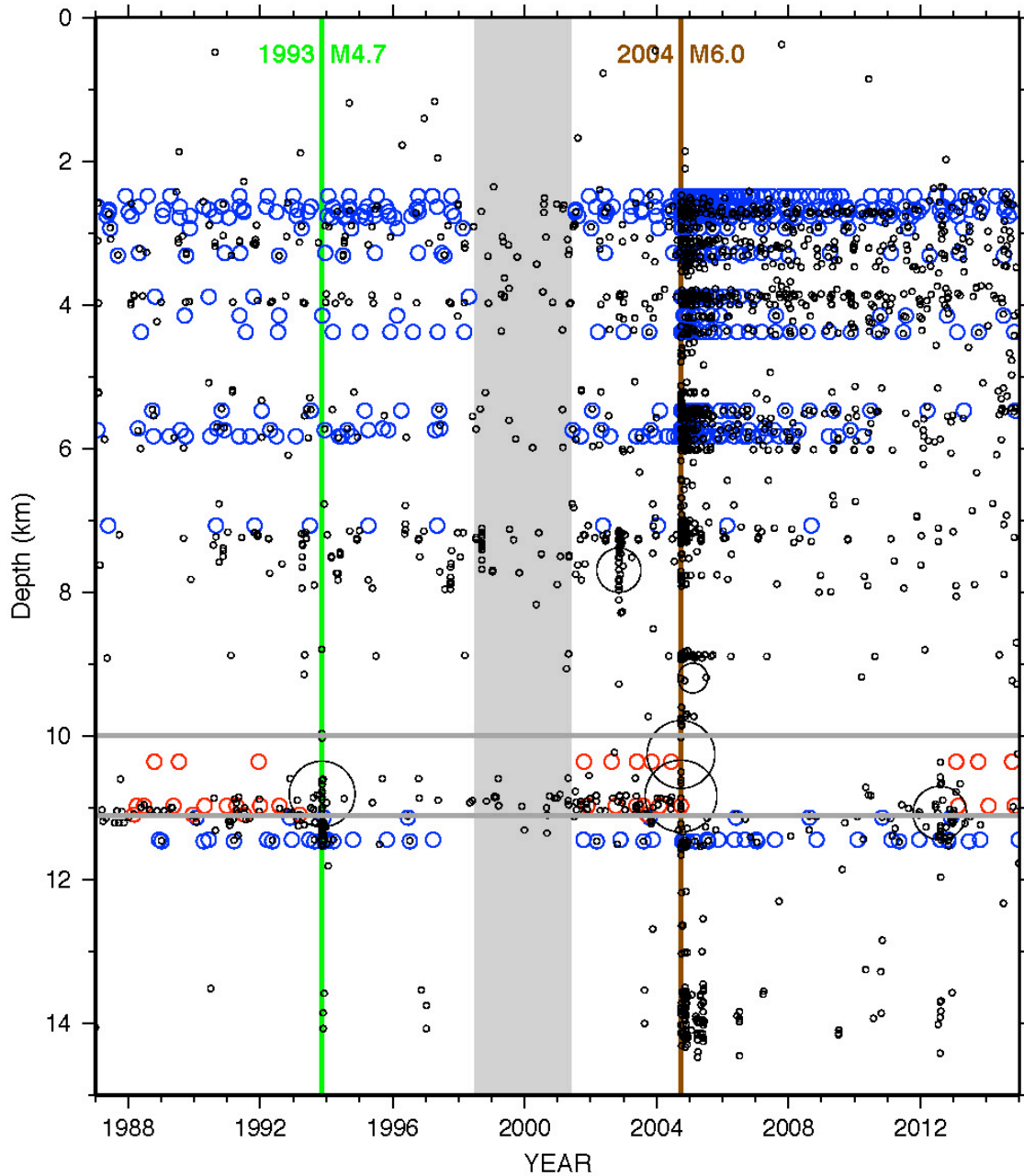


Figure 3. Time versus depth of REQ and other seismicity in the focus region shown in **Figure 1**. Red are ON-OFF REQs. Blue are other REQs. Black are non-REQ seismicity in the focus region with $M \geq 3.5$ events shown as larger circles. Green and Brown lines and Gray band are as in **Figure 2**. Gray horizontal lines are approximate depth range of the ON-OFF zone. Activity of the non-REQ seismicity in the ON-OFF zone between ~ 10 and 11 km shows a general decrease during the shut-off period of the ON-OFF REQs.

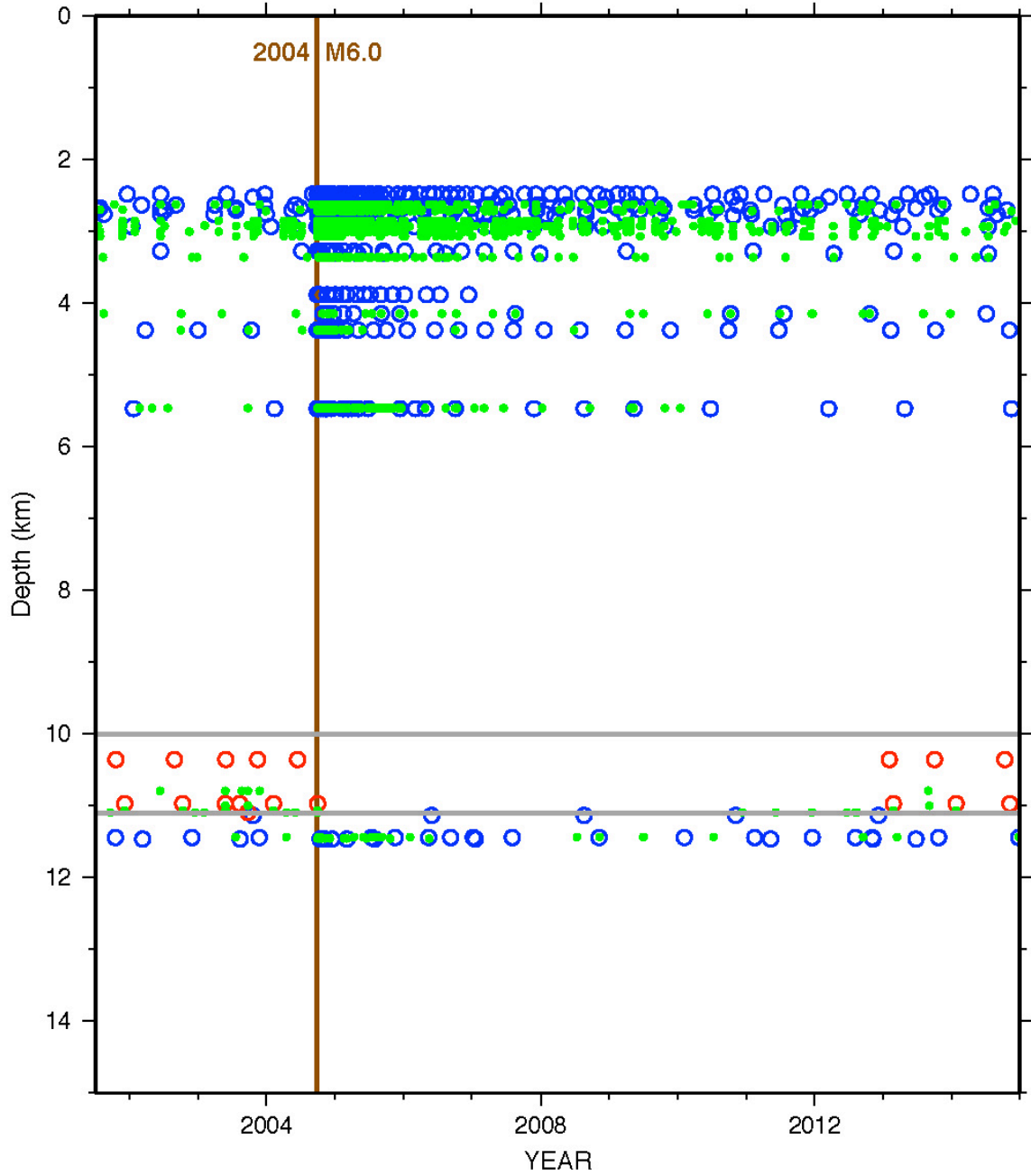


Figure 4. Comparison of REQ and similar event behaviors during the period of continuous recording. Green circles are times and depths of seismicity similar to REQ events at a relaxed criteria of maximum cross-correlation value 0.80. Other lines and colors are as in **Figure 3**. Similar events down to the relaxed 0.80 criteria were also shut-off during the REQ shut-off period, arguing against waveform distortions as a possible reason for apparent REQ shut-offs.

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